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U–Pb and $^{40}Ar/^{39}Ar$ mineral ages from Cape North, northern Cape Breton Island: implications for accretion of the Avalon Composite Terrane

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Isotopic studies have been used to determine protolith and tectonothermal ages in rocks of the Cape North and Money Point groups and two plutons, that form part of the Avalon Composite Terrane. Colourless, euhedral zircon crystals from low-grade metarhyolite in the Money Point Group record a concordant U–Pb age of 427.5 ± 4 Ma, which is interpreted to date the time of extrusion. This provides a maximum age of middle Silurian polyphase deformation and concomitant greenschist–amphibolite-facies metamorphism that affected the Cape North area. The eastern half of a major, sinistral, positive flower structure. Monazite from the Cape North granite, intruded during peak metamorphic conditions, yielded nearly concordant data with a $^{207}Pb/^{235}U$ age of 414 ± 3 Ma. This dates the time of crystallization of the Cape North granite. Metamorphic hornblende from the Cape North and Money Point groups records variably discordant $^{40}Ar/^{39}Ar$ age spectra that define plateau and (or) isotope correlation ages of ca. 380–390 Ma. Muscovite from these units displays generally concordant spectra that define plateau ages ranging between ca. 365 and 375 Ma. Muscovites from the syntectonic Cape North granite and the posttectonic Relay Station granite record plateau ages of ca. 380–382 Ma. The $^{40}Ar/^{39}Ar$ ages suggest that relatively rapid postmetamorphic cooling occurred during the Devonian. These isotopic results and petrological data indicate that burial of the Cape North units to ca. 18 km, metamorphism, uplift, and erosion occurred in ca. 60 Ma. Such rates are comparable with those recorded in modern transpressive tectonic regimes. The calc-alkaline nature of the Money Point volcanic rocks suggests derivation above a subduction zone. A correlative Silurian–Devonian tectonothermal event recorded in southern Newfoundland probably records the accretion of the Avalon Composite Terrane with the Dunnage Zone.

Les résultats d'analyses isotopiques ont été utilisés pour déterminer le protolite et les âges tectonothermiques des roches des groupes de Cape North et Money Point et de deux plutons qui forment une partie du terrane composite d'Avalon. Les cristaux de zircon incolores, automorphes, extraits de la métarhyolite faiblement métamorphisée du Groupe de Money Point, fournissent un âge U–Pb concordant de 427,5 ± 4 Ma, et interprété comme date de l'extrusion. Cet âge maximum place au Silurien moyen la déformation polyphasée et l'évènement métamorphique concomittant, de faciès des schistes verts – amphibolites, qui ont dérangé les roches de la région de Cape North dans la moitié orientale de l'importante structure senestre et positive en bouquets de fleur. La monazite, extraite du granite de Cape North mis en place durant l'apogée métamorphique, a fourni des âges $^{207}Pb/^{235}U$ presque concordants de 414 ± 3 Ma. Cette date détermine le temps de la cristallisation du granite de Cape North. La hornblende d'origine métamorphique des groupes de Cape North et de Money Point a fourni des spectres d'âges $^{40}Ar/^{39}Ar$ variables et discordants qui définissent des âges plateau et (ou) de corrélation isotopique compris entre environ 380–390 Ma. Dans ces mêmes unités, la muscovite produit généralement des spectres concordants qui définissent des âges plateau oscillant entre environ 365 et 375 Ma. Les muscovites du granite de Cape North syntectonique, et du granite de Relay Station posttectonique, fournissent des âges plateau autour de 380–382 Ma. Les âges $^{40}Ar/^{39}Ar$ suggèrent un refroidissement postmétamorphique relativement rapide durant le Dévonien. Ces résultats isotopiques et données pétrologiques révèlent que les évènements de l'enfouissement des unités de Cape North à environ 18 km, métamorphisme, soulèvement et érosion se sont produits dans un intervalle de 60 Ma, approximativement. Ces taux sont comparables à ceux déduits des régimes tectoniques de transpression actuels. La nature calco-alcaline des roches volcaniques du Groupe de Money Point témoigne d'une origine au-dessus d'une zone de subduction. Un évènement tectonothermique dans le sud de Terre-Neuve, mis en corrélation avec le Silurien–Dévonien, indique probablement une accrétion du terrane composite d'Avalon avec la zone de Dunnage.

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Introduction

Brown (1973) correlated the Aspy Fault in northern Cape Breton Island with the Cape Ray Fault in southwestern Newfoundland and interpreted it as a cryptic Paleozoic suture along which Iapetus had been eliminated through the collision of Laurentia and Avalonia. A modification of Brown's ideas has been favoured by Barr and Raeside (1986, 1989), Loncarevic *et al.* (1989), and Marillier *et al.* (1989), who subdivided Cape Breton Island into four terranes, namely Blair River, Aspy, Bras d'Or, and Mira (Fig. 1), which were correlated with the Humber, Dunnage, Gander, and Avalon terranes in Newfoundland, respectively. Alternatively, Keppie (1979, 1982, 1990) correlated rock units across the Aspy Fault and inferred that they all are parts of the Avalon Zone (Fig. 1). Central to the contrasting interpretations is the reliability of lithostratigraphic correlations across Cape Breton Island because no paleontological and few definitive geochronological ages are available. In an attempt to help resolve the conflicting models, an integrated geochronological study has been carried out in the pivotal Cape North area. These results are presented here

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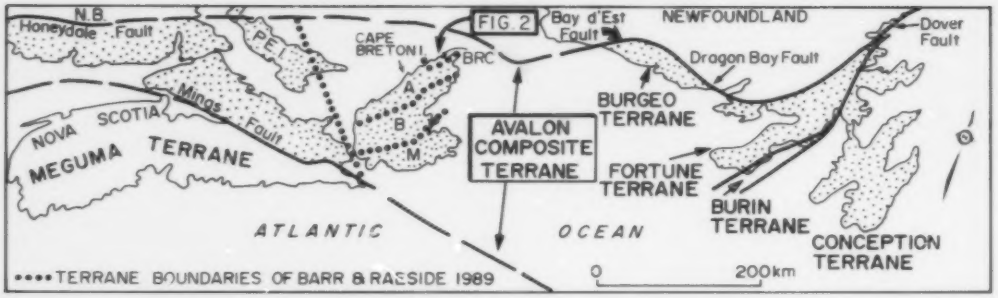

FIG. 1. Generalized map of the northern Appalachian orogen, showing the location of the Cape North area and Cape Breton Island in relation to the Avalon Composite Terrane of Keppie and Dallmeyer (1989) and the "terrane boundaries" and "terranes" proposed by Barr and Raeside (1989). BRC, Blair River complex; A, Aspy terrane; B, Bras d'Or terrane; M, Mira terrane.

and indicate that a Silurian volcano-sedimentary unit was affected by an intense Silurian–Devonian tectonothermal activity previously thought to be of Precambrian age. This Silurian unit is most closely correlated with the La Poile Group in southern Newfoundland, which overlies rocks of Avalonian affinity (Dunning and O'Brien 1989). The Silurian–Devonian tectonothermal activity is inferred to be associated with the accretion of the Avalon Composite Terrane to Laurentia.

Geological setting

Pre-Carboniferous crystalline rocks exposed in the northern Cape Breton Highlands of Nova Scotia may be subdivided into three main lithostratigraphic units (Figs. 2, 3). The oldest rocks (Blair River complex, part of the Pleasant Bay Complex) consist of lenses of polydeformed, retrogressed granulites (biotite and quartzo-feldspathic gneisses) that occur within younger granitoid gneisses (Barr *et al.* 1987*a*; Currie 1987). Eastern contacts of these older gneisses are defined by steeply dipping, ductile shear zones (e.g., Wilkie Brook Fault) that separate them from medium- to high-grade, polydeformed, pelitic and semipelitic gneisses, quartzites, and marbles (Cape North Group; Figs. 2, 3) (Macdonald and Smith 1980; Smith and Macdonald 1983; Barr *et al.* 1987*a*). The Cape North Group is followed eastwards by low- to medium-grade pelitic–psammitic schist, volcanic rocks, and pyroclastic rocks (Money Point Group) that record the same polyphase deformation as the Cape North Group (Figs. 2, 3) (Keppie 1979; Macdonald and Smith 1980). Boundaries between the Cape North and Money Point groups are steeply westward dipping, and Macdonald and Smith (1980, p. 3) described contacts as "... relatively sharp and although complicated by granitic injection, showing no evidence for either an erosional or tectonic break." However, contacts in coastal exposures are obscured by granite sheets, and inland contacts are not exposed. Based on the predominantly andesitic nature of the volcanic rocks and their major-element chemistry, Macdonald and Smith (1980) suggested that they represent a tholeiitic–calcalkaline suite erupted in a volcanic-arc tectonic setting. The metamorphic and igneous units are unconformably overlain by the Late Devonian Fisset Brook Formation, the Tournaisian Horton Group, and the Visean Windsor Group.

The Blair River complex records a complex, polyphase deformation associated with two progressive high-grade metamorphic events followed by retrogressive metamorphism (Currie 1987). The age of deformation and metamorphism in the Blair River complex is poorly constrained. A 918^{+78}_{-179} Ma lower intercept of the U–Pb chord on zircons from the Lowland Brook syenite (Barr *et al.* 1987*a*; Keppie *et al.* 1991*b*) suggests that at least some of the deformation and metamorphism is Precambrian.

In the Cape North area, the Cape North and Money Point groups have been deformed by five distinct deformational events (Macdonald and Smith 1980): D_1: subhorizontal, isoclinal folding; regional phyllitic to gneissic foliation and penetrative, subhorizontal lineation under prograde, greenschist-facies metamorphism; D_2: subhorizontal, mesoscopic folds; moderately steeply dipping, penetrative crenulation foliation, and subhorizontal lineation; immediately followed by peak, middle greenschist (east) – upper amphibolite (west) facies metamorphic conditions with mapped isograds subparallel to lithological contacts (Figs. 2, 3); D_3–D_5: local kink bands and megascopic, generally upright folds under retrograde metamorphic conditions.

Lineations L_1 and L_2 are parallel to one another and to the long axes of stretched clasts in metaconglomerate and metatuff with $X:Y:Z$ ratios of 12:2:1. In the Cape North Group and the Cape North pluton the S_1 and S_2 fabrics appear to be spatially related to ductile shear zones, and when interpreted as C–S fabrics they indicate a sinistral sense of shear.

Reynolds *et al.* (1989) published an internally discordant, $^{40}Ar/^{39}Ar$ spectrum for porphyroblastic hornblende in a metabasite within the Money Point Group but provided no age or isotope correlation data. They also published discordant $^{40}Ar/^{39}Ar$ spectra that defined total-gas ages of 429 ± 3, 381 ± 3, and 362 ± 3 Ma for metamorphic biotite in the Money Point and Cape North groups west of the Aspy Fault (Fig. 2).

The three main lithostratigraphic units in the northern Cape Breton Highlands have been intruded by a variety of plutonic rocks. These include variably foliated anorthosite, gabbro, monzodiorite, syenite, and monzonite and unfoliated granodiorite and granite. The oldest dated pluton (Lowland Brook syenite) intrudes both the Blair River complex and the anorthosite and was subsequently affected by an upper amphibolite facies metamorphism (Barr *et al.* 1987*b*). This syenite yielded U–Pb zircon data that define a chord between 1172^{+175}_{-73} and 918^{+78}_{-179} Ma, inferred to date the time of intrusion and metamorphism, respectively (Fig. 2) (Barr *et al.* 1987*b*; Keppie *et al.* 1991*b*). Other isotopically dated igneous rocks in the area include the following:

(1) The variably foliated, syn-D_2, Gulch Brook microgran-

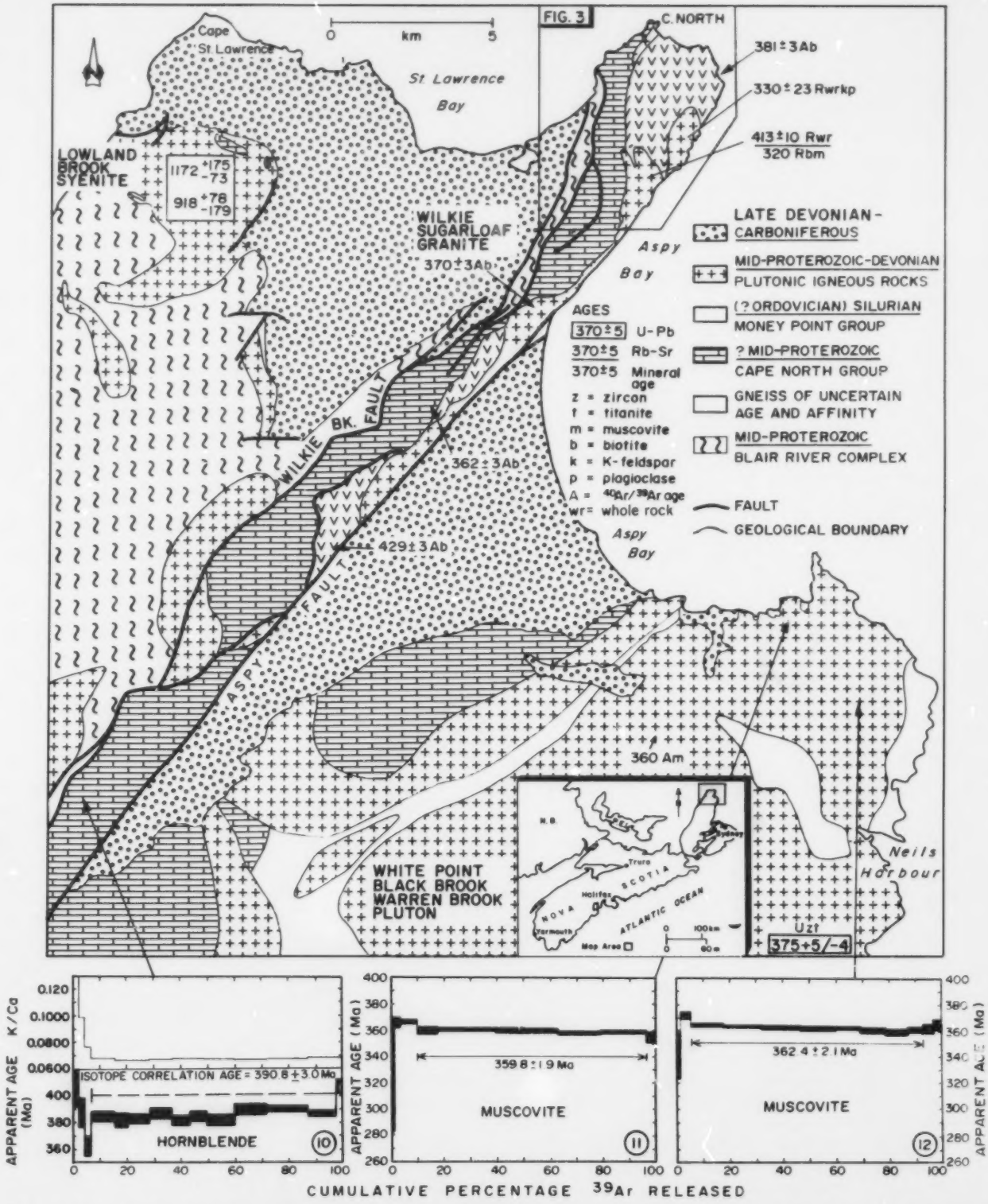

FIG. 2. Generalized geological map of northern Cape Breton Highlands, showing published isotopic age determinations, the location of Fig. 3, and three new $^{40}Ar/^{39}Ar$ incremental release age spectra with cumulative percentage of ^{39}Ar released plotted against apparent age in millions of years (Ma) and apparent K/Ca ratios. Plateau ages and isotope correlation ages for the part of the spectrum defined by solid or broken horizontal lines, respectively, are listed on each spectrum. Intralaboratory, analytical uncertainties (2σ) are represented by the vertical width of bars. R, Rb–Sr age.

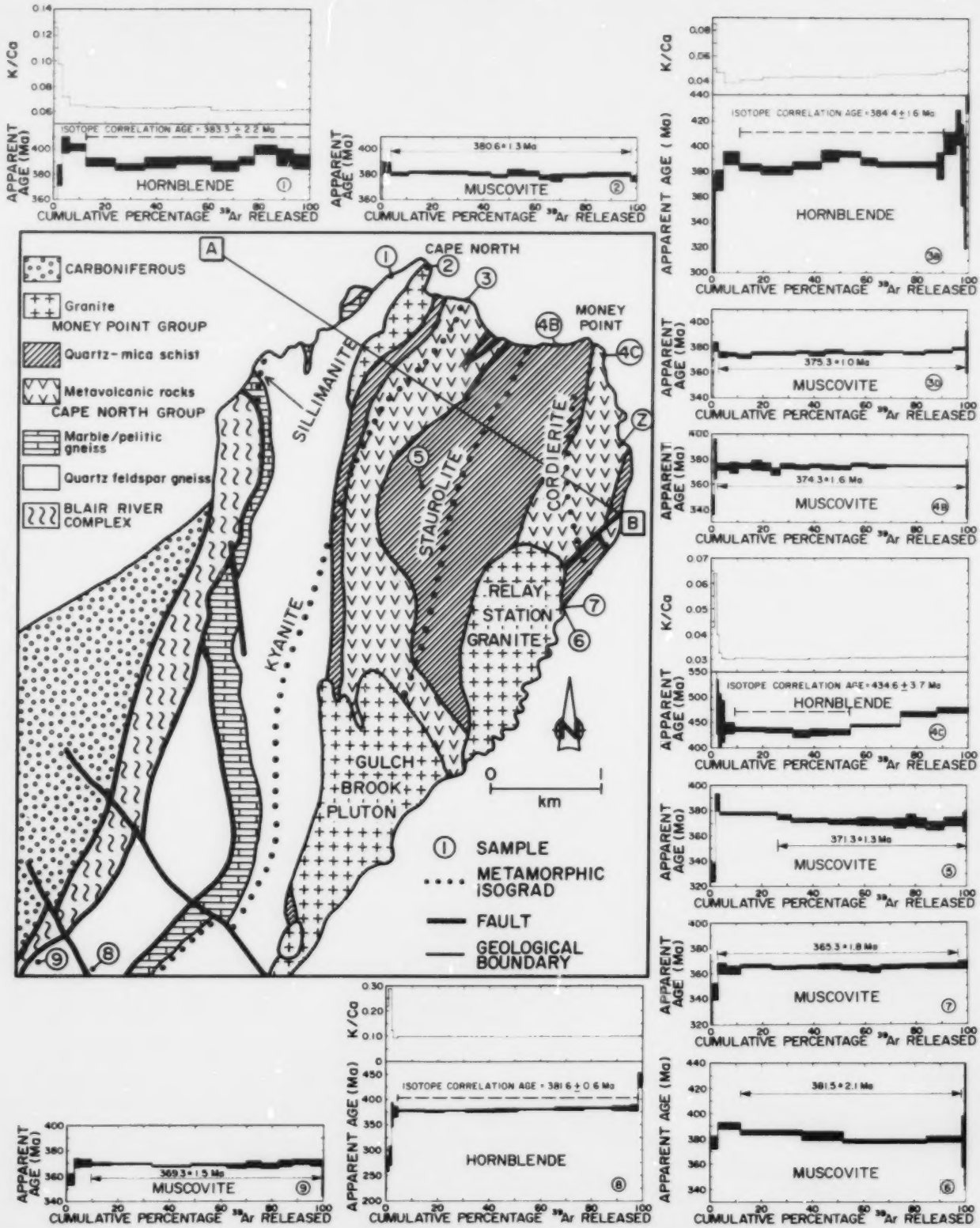

FIG. 3. Geological map of the Cape North area (modified after Macdonald and Smith 1980), showing $^{40}Ar/^{39}Ar$ incremental release age spectra (see Fig. 2 for details). A–B is the location of the cross section shown in Fig. 8. Z, the location of the U–Pb zircon sample.

ite pluton (Fig. 3), which yielded a seven-point, Rb–Sr whole-rock isochron of 413 ± 10 Ma (mean square of weighted deviates (MSWD) = 23.3; initial $^{87}Sr/^{86}Sr$ = 0.70446 ± 0.00043) that was tentatively interpreted as dating igneous crystallization (Keppie and Halliday 1986).

(2) The unfoliated, posttectonic Relay Station granitic pluton (Fig. 3), which yielded a nine-point, Rb–Sr whole-rock – mineral isochron of 330 ± 23 Ma with an initial $^{87}Sr/^{86}Sr$ = 0.7053 ± 0.0022 (Fig. 2) (MSWD not reported; Cormier 1980) that was interpreted as dating igneous crystallization. Biotite from a similar postkinematic granite (Wilkie Sugarloaf granite) has yielded an internally discordant, $^{40}Ar/^{39}Ar$ spectrum with a total-gas age of 370 ± 3 Ma (Fig. 2) (Reynolds *et al.* 1989).

(3) Approximately 10 km east of the Aspy Fault, gneisses of uncertain affinity are intruded by an extensive stock of generally massive, biotite (± muscovite) granite–granodiorite (White Point – Black Brook – Warren Brook pluton; Fig. 2). It is locally penetratively deformed in narrow ductile shear zones (Wiebe 1975; Barr *et al.* 1982). The Black Brook pluton has yielded isotopic ages of 375^{+5}_{-4} Ma (Fig. 2) (U–Pb zircon upper intercept and concordant monazite ages; Dunning *et al.* 1990*a*) and ca. 360 Ma (slightly discordant $^{40}Ar/^{39}Ar$ muscovite total-gas age; Reynolds *et al.* 1989). These data indicate rapid cooling following intrusion.

Experience suggests that Rb–Sr ages be treated with caution. Furthermore, published $^{40}Ar/^{39}Ar$ data from the Cape North area are discordant, no isotope correlation data have been provided, and total-gas ages range from ca. 430 to 360 Ma. So despite the assertion of Reynolds *et al.* (1989, p. 2087) that "... the argon data thus suggest that cooling was rapid following Late Silurian – Devonian (Acadian) high grade metamorphism and intrusion and prior to some late-stage intrusive activity," in our view it remains uncertain whether these dates are related to regional tectonothermal events or to reheating associated with plutonism. Thus, ages defining the geological history of the Cape North area are unconstrained by existing data.

Analytical techniques

U–Pb

A rhyolite sample from the Money Point Group and a sample of the Cape North granite were crushed using a jaw crusher and disc mill, and minerals were separated using a Wilfley Table, heavy liquids, and a Frantz Isodynamic separator at the Royal Ontario Museum. All crushing and grinding plates were removed and cleaned with alcohol and an electric brush prior to each use to avoid any possibility of contamination, even single grain. Zircon concentrates were further separated into magnetic and size fractions, but only the least paramagnetic fractions were used during the final selection of the highest quality grains under a binocular microscope (Table 1). All grains selected were then abraded prior to analysis (Krogh 1982) to reduce or eliminate surface-correlated lead loss associated with geologically leached surfaces. Zircons were dissolved and analyzed as described in Krogh (1973) with the exception that smaller dissolution capsules and columns were used in some cases (i.e., capsules with 0.5 cm^3 vs. >5 cm^3, and columns with 0.05 cm^3 vs. 0.5 cm^3 of resin). Total procedure lead blanks of 12 pg were measured during the period of analyses reported. A mixed $^{205}Pb–^{235}U$

TABLE 1. U–Pb isotopic data for zircon from rhyolite in the Money Point Group and monazite from the Cape North Pluton

Fraction	Weight (mg)	U (ppm)	Common Pb[a] (pg)	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb^c}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$ age (Ma)
Zircon									
1. N0, M0, clear, euhedral least cracked, abraded	0.112	385	10	0.05538	17 634	0.2472	0.06841	0.5224	428
2. Prisms and full-length fluid inclusions, abraded	0.136	347	45	0.05616	4 479	0.2670	0.07012	0.5429	459
3. N0, M0, euhedral, cracked, abraded	0.165	419	21	0.05556	13 419	0.2542	0.06741	0.5164	435
4. N0, M0, long crystals with fluid inclusions, not abraded	0.204	475	66	0.05570	5 241	0.2596	0.05962	0.4579	440
Monazite									
5. Nine small crystals, not abraded	0.017	1050	16	0.05492	4 780	0.6654	0.06654	0.5039	409, 415[d], 414[e]

NOTES: N, nonmagnetic; M, magnetic; following number refers to degree of tilt on the Frantz isodynamic separator at full current. All grains except 4 are abraded to remove surface-correlated lead loss. ^{238}U decay constant = 0.15513 × 10 ^{9}/year. ^{235}U decay constant = 0.98485 × 10 ^{9}/year. $^{238}U/^{235}U$ = 137.88.

[a]Total common lead present; includes components from sample and blank.

[b]Corrected for fractionation, blank, and common lead in the spike sample. The isotopic composition of common lead in the sample is calculated using the Stacey and Kramers model (1975). All samples were corrected for 12 pg of blank lead; in correcting for fractionation, $^{207}Pb/^{206}Pb$ and $^{206}U/^{238}U$ are increased by 0.13% per mass unit.

[c]Measured values corrected for spike contribution.

[d]$^{206}Pb/^{238}U$ age.

[e]$^{207}Pb/^{235}U$ age.

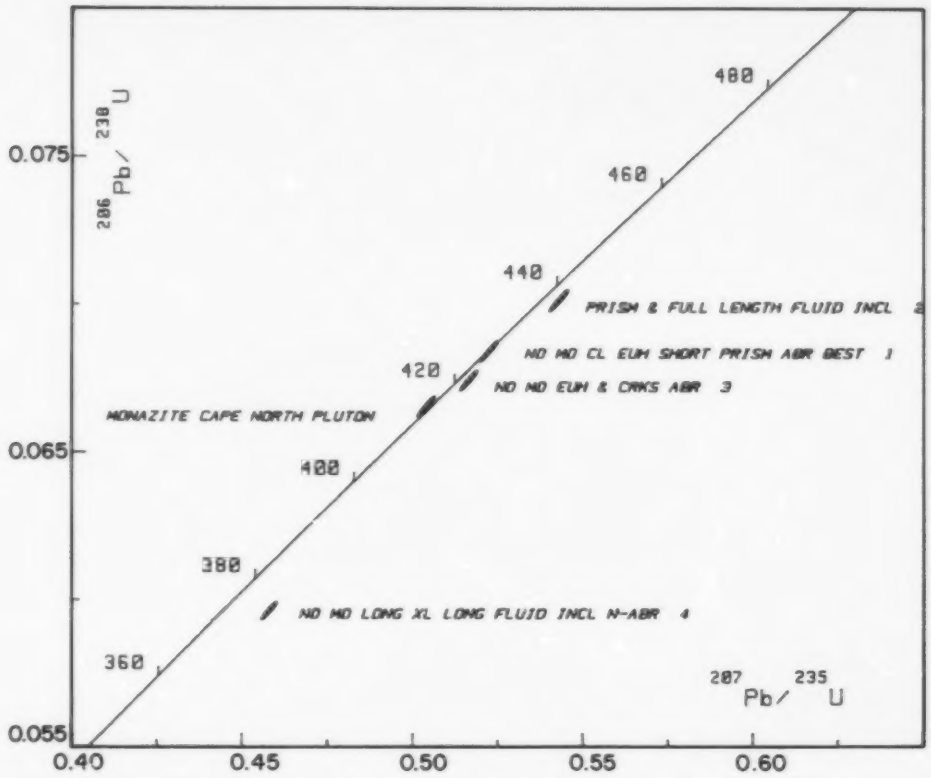

FIG. 4. U–Pb concordia diagram for zircon separated from a Money Point rhyolite sample (Z) and a monazite from a sample from the Cape North granite from locality 2; see Fig. 3 for locations and Table 1 for explanation of abbreviations.

isotopic tracer was added prior to a 5 day digestion at 220°C. Monazite was dissolved in an oven in 6 N HCl contained in Teflon bombs, and Pb and U were separated using HBr chemistry. Lead and uranium were analyzed sequentially on the same filament using first silica gel and then Ta_2O_5. Ratios of ^{207}Pb to ^{204}Pb were measured using a Daly detector in an integrating mode, and other lead and uranium isotopes were measured on a Faraday cup. Analytical uncertainties due to measurement errors alone are less than 1.0 and 0.2% (2σ) for the Pb/U and $^{207}Pb/^{206}Pb$ ratios, respectively, corresponding to about ±4 Ma in the 207/206 age. The size of the error ellipses in Figure 4 reflects this uncertainty.

$^{40}Ar/^{39}Ar$

Techniques used during $^{40}Ar/^{39}Ar$ analysis generally followed those described in detail by Dallmeyer and Keppie (1987). Pure mineral concentrates (>99%) were irradiated for 40 h at 1000 kW in the central thimble position of the United States Geological Survey TRIGA reactor in Denver, Colorado. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with the MMhb-1 hornblende standard (519 Ma; Alexander *et al.* 1978). The samples were heated incrementally until fused with a radio frequency (RF) generator. Each heating step was maintained for 30 min. Measured isotopic ratios were corrected for the effects of mass discrimination, total system blanks, and interfering isotopes produced during irradiation with factors reported by Dalrymple *et al.* (1981) for the reactor used in the present study. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977). Intralaboratory uncertainties are reported to 2σ. A "plateau" is considered defined if the ages recorded by two or more contiguous gas fractions each representing >4% of the total ^{39}Ar evolved (and together constituting >50% of the total quantity of ^{39}Ar evolved) are mutually similar within a ±1% uncertainty. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios may be calculated through the relationship 0.518 (±0.005) × ($^{39}Ar/^{37}Ar$) corrected. Where appropriate, total-gas and (or) plateau $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlations have been calculated. Regression techniques generally followed the two-error methods outlined by York (1969).

Results

U–Pb

A sample of metarhyolite was collected on the coast about 1 km southeast of Money Point for U–Pb dating (sample Z, Fig. 3). The rhyolite is interbedded with felsic and mafic tuffs of the Money Point Group and displays a penetrative S_1 cleavage that has been refolded by S_2 crenulations. The rhyolite contains phenocrysts of unaltered to cloudy albite and resorbed quartz in a fine-grained matrix of quartz, feldspar, and muscovite (aligned along the S_1 cleavage) together with minor chlorite and opaque minerals. The mineralogy of the rhyolite and the adjacent tuffs suggests a lower greenschist facies metamorphism.

Zircon crystals separated from the rhyolite sample were separated into four populations, including (1) nonmagnetic, clear, euhedral, short crystals; (2) nonmagnetic prisms with

fluid inclusions along the entire length of each crystal; (3) cracked, nonmagnetic, euhedral crystals; and (4) nonmagnetic, long crystals with long fluid inclusions. Grains with full-length cracks or fluid inclusions were selected in an attempt to avoid inherited cores. Each fraction was abraded except for that of population 4. Results of the isotopic analysis are listed in Table 1 and plotted in a concordia diagram (Fig. 4). Of the three abraded fractions, only the short euhedral fraction (population 1) plots on concordia, with an age of 427.5 ± 4 Ma. Population 2 is slightly discordant, with a $^{207}Pb/^{206}Pb$ age of 458.5 Ma. Population 3 is slightly discordant, with a $^{207}Pb/^{206}Pb$ age of 434.9 Ma. Population 4 is also discordant, with a $^{207}Pb/^{206}Pb$ age of 440.4 Ma. A small amount of inherited zircon is apparently present in all but fraction 1.

Monazite was separated from a sample of the foliated Cape North granite (locality 2, Fig. 3). The foliation was classified as D_2 by Macdonald and Smith (1980); however, in discrete C−S shear zones it may be correlated with the C planes. The granite consists of quartz, feldspar, muscovite, and biotite, with accessory opaque minerals and apatite. Data for the monazite plots above the concordia curve (by 1.6%), with $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$ ages of 415, 414, and 409 Ma, respectively (Table 1; Fig. 4).

$^{40}Ar/^{39}Ar$

Samples for $^{40}Ar/^{39}Ar$ age dating were collected from a range of metamorphic grades and for various plutonic igneous rocks exposed in the Cape North region. Five hornblende and nine muscovite concentrates from the Cape North and Money Point groups and associated intrusions have been analyzed. Sample localities and incremental release age spectra are displayed in Figs. 2 and 3. The $^{40}Ar/^{39}Ar$ analytical data are listed in Tables 2 and 4. Apparent K/Ca ratios recorded by gas increments released from the muscovite concentrates are very large and have considerable associated uncertainties. For this reason, and because the ratios show no significant or systematic intrasample variation, apparent K/Ca spectra are not presented with the muscovite age spectra in Figs. 2 and 3.

Hornblende

Hornblende concentrates were prepared from foliated amphibolite collected within the Cape North Group at locations 1, 8, and 10. That from sample 1 displays an internally discordant $^{40}Ar/^{39}Ar$ age spectrum that defines a total-gas age of 392.9 ± 11.8 Ma. The 695−820°C increments are characterized by similar apparent K/Ca ratios. These increments yield a $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlation (MSWD = 0.57) corresponding to an age of 383.3 ± 2.2 Ma and an inverse ordinate intercept of 335.9 ± 24.3 (Table 3). The concentrate from sample 8 displays an internally discordant $^{40}Ar/^{39}Ar$ spectrum corresponding to a total-gas age of 378.7 ± 3.6 Ma. The 660−820°C increments have similar apparent K/Ca ratios and record apparent ages that are similar and yield a plateau of 380.4 ± 2.4 Ma. The plateau data correspond to an isotope correlation (MSWD = 0.28) that defines an age of 381.6 ± 0.6 Ma and an inverse ordinate intercept of 264.9 ± 13.6. The hornblende concentrate from a foliated amphibolite (sample 10) displays an internally discordant $^{40}Ar/^{39}Ar$ spectrum corresponding to a total-gas age of 384.7 ± 5.7 Ma (Table 2; Fig. 2). The 645−745°C increments have similar apparent K/Ca ratios and yield a $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlation (MSWD = 1.02) corresponding to an age of 390.8 ± 3.0 Ma and an inverse ordinate intercept of 285.9 ± 12.6 (Table 3).

Foliated amphibolite was collected from locations 3 and 4 within the Money Point Group. The hornblende concentrate from sample 3B is characterized by an internally discordant age spectrum (Fig. 3) yielding a total-gas age of 387.7 ± 7.9 Ma. The 650−735°C increments have similar apparent K/Ca ratios and yield an isotope correlation (MSWD = 1.2) that defines an age of 384.4 ± 1.6 Ma and an inverse ordinate intercept of 282.9 ± 26.3. The concentrate from sample 4C also displays an internally discordant spectrum and yields a total-gas age of 461.7 ± 8.5 Ma. The 700°C-fusion increments are characterized by similar apparent K/Ca ratios; however, no combination of incremental data sets yields a meaningful isochron with an MSWD < 2.0. The 700−770°C increments yield an isotope correlation age of 434.6 ± 3.7 Ma, but the MSWD (=2.2) is unacceptably large.

Muscovite

A muscovite concentrate from schist within the Cape North Group (sample 9) displays an internally concordant $^{40}Ar/^{39}Ar$ spectrum corresponding to a plateau age of 369.3 ± 1.5 Ma (Table 4; Fig. 3). Muscovite concentrates from two samples of schist from the Money Point Group (3D and 4B) are characterized by internally concordant $^{40}Ar/^{39}Ar$ spectra that yield plateau ages of 375.3 ± 1.0 and 374.3 ± 1.6 Ma, respectively (Table 4; Fig. 3). Sample 5, also collected within schist of the Money Point Group, yields a slightly more discordant muscovite age spectrum (Fig. 3); however, the 530−730°C increments record similar apparent ages that correspond to a plateau of 371.3 ± 1.3 Ma. Sample 7 was collected within lower grade portions of the Money Point Group, ~20 m north of the contact with the Relay Station granite. Here the regional S_1 foliation is defined by preferred alignment of intergrowths of very fine-grained muscovite and biotite. This fabric is overgrown by larger, randomly oriented porphyroblasts of muscovite and, locally, biotite. A concentrate of the coarser grained porphyroblastic muscovite was prepared from sample 7. This is characterized by an internally concordant age spectrum yielding a plateau age of 365.3 ± 1.8 Ma (Table 4; Fig. 3).

A muscovite concentrate from foliated granite of the Cape North pluton (sample 2) displays an internally concordant $^{40}Ar/^{39}Ar$ spectrum corresponding to a plateau age of 380.6 ± 1.3 Ma (Table 4; Fig. 3). A muscovite concentrate from a sample of massive granite collected near the margin of the Relay Station pluton (sample 6) yields a plateau age of 381.5 ± 2.1 Ma (Table 4; Fig. 3). Two muscovite concentrates collected within massive granite of the White Point pluton display internally concordant spectra corresponding to plateau ages of 362.4 ± 2.1 and 359.8 ± 1.9 Ma (Table 4; Fig. 2).

Interpretation

U−Pb

The single concordant inheritance-free zircon population (1) provides a precise unambiguous age of 427.5 ± 4 Ma for the time of crystallization of the rhyolite in the Money Point Group. The variation in the $^{207}Pb/^{206}Pb$ age indicates that a small amount of inherited material is present in most of the analyzed populations, even though each was selected to avoid grains with inherited cores.

The monazite data from the Cape North granite plots above concordia because excess ^{230}Th was incorporated at the time of its formation. This thorium decays to produce an excess of ^{206}Pb and an anomalous $^{206}Pb/^{238}U$ age. In such cases, the $^{207}Pb/^{235}U$ age (414 ± 3 Ma) is considered the best estimate

TABLE 2. $^{40}Ar/^{39}Ar$ analytical data for incremental heating experiments on amphibole concentrates from the area of Cape North, Cape Breton Highlands, Nova Scotia

Release temp. (°C)	$(^{40}Ar/^{39}Ar)_{meas}$[a]	$(^{36}Ar/^{39}Ar)_{meas}$[a]	$(^{37}Ar/^{39}Ar)_{corr}$[b]	^{39}Ar (% of total)	^{40}Ar (%, nonatmos.)[c]	$^{36}Ar_{calc}$ (%)	Apparent age (ma)[d]
			CAPE NORTH GROUP				
			Sample 1: J = 0.006681				
535	80.24	0.17668	3.981	1.51	35.30	0.64	313.5±45.1
630	78.39	0.15033	5.150	1.66	43.84	0.98	374.2±27.2
650	50.52	0.04562	6.993	2.93	74.41	4.38	406.1±8.8
680	41.66	0.01725	7.697	6.27	89.24	12.76	402.3±6.3
695	39.36	0.01369	7.866	11.37	91.31	16.43	390.3±3.4
705	38.53	0.01230	7.926	11.27	92.21	18.43	386.3±2.9
715	38.05	0.00952	7.944	12.71	94.27	23.85	389.6±4.3
725	40.66	0.01774	7.847	13.71	88.64	12.65	391.3±5.2
740	38.34	0.01160	8.170	10.35	92.76	20.14	386.7±4.4
755	38.45	0.01079	8.189	6.47	93.41	21.71	390.2±7.0
770	38.85	0.00899	8.205	8.78	94.85	26.12	399.2±7.1
790	40.47	0.01631	8.170	6.10	89.70	14.33	393.9±8.4
820	41.94	0.02325	8.112	6.69	85.05	9.98	388.2±8.3
Fusion	4294.62	13.59910	10.020	0.19	6.45	0.02	1898.2±291.8
Total	49.20	0.04553	7.862	100.00	89.08	16.99	392.9±11.8
			Sample 8: J = 0.008418				
475	54.80	0.12038	2.243	1.04	35.40	0.51	273.2±15.0
525	41.51	0.07092	1.693	1.14	49.82	0.65	289.8±18.9
575	44.55	0.06314	3.977	0.63	58.82	1.71	360.5±13.6
625	35.09	0.02867	5.162	1.86	77.02	4.90	370.9±8.8
660	29.22	0.0640	5.001	10.30	94.88	21.26	379.5±2.1
680	28.97	0.00586	5.019	7.99	95.40	23.30	378.4±2.2
695	28.95	0.00551	5.016	8.49	95.75	24.75	379.4±1.3
710	28.47	0.00408	5.009	11.37	97.16	33.40	378.7±3.0
725	28.40	0.00355	5.008	8.57	97.70	38.35	379.8±3.5
740	38.26	0.00318	5.034	14.68	98.09	43.06	380.7±1.5
755	28.50	0.00340	5.016	11.38	97.87	40.18	381.6±3.1
775	28.56	0.00315	4.963	10.56	98.12	42.84	383.2±1.4
795	28.76	0.00419	4.952	7.31	97.06	32.16	381.8±4.3
820	30.64	0.00966	4.970	3.20	91.81	13.99	379.7±6.4
Fusion	168.26	0.46073	5.004	1.48	19.32	0.30	437.6±14.9
Total	31.41	0.01397	4.933	100.00	93.90	31.57	378.7±3.6
Total without 475–625°C, 820°C, and fusion data				90.64			380.4±2.4
			Sample 10: J = 0.006681				
525	78.07	0.13758	2.830	2.17	48.18	0.59	405.2±14.4
600	55.79	0.06966	5.106	2.06	63.81	2.10	386.2±12.3
630	49.96	0.05914	6.574	2.37	65.14	3.18	368.1±18.3
645	39.13	0.01475	7.389	8.84	90.36	14.33	384.5±3.5
660	41.73	0.02479	7.509	4.86	83.64	8.66	379.9±4.6
675	39.85	0.01785	7.516	8.09	88.27	12.05	382.7±3.9
685	38.91	0.01299	7.495	8.36	91.66	16.50	387.5±3.6
695	39.56	0.01581	7.417	6.46	89.54	13.41	384.7±4.3
705	38.52	0.01198	7.414	6.36	92.34	17.71	386.5±3.1
710	37.97	0.01167	7.440	10.10	92.47	18.23	382.0±4.0
720	37.22	0.00636	7.514	12.15	96.56	33.81	390.2±3.9
730	38.00	0.00885	7.450	15.30	94.67	24.07	390.5±2.8
745	37.32	0.00775	7.348	10.35	95.43	27.13	386.9±3.3
Fusion	41.12	0.01752	7.443	2.54	88.85	12.15	396.0±10.2
Total	40.08	0.01779	7.280	100.00	89.77	18.75	384.7±5.7
			MONEY POINT GROUP				
			Sample 3B: J = 0.006681				
525	121.28	0.31740	5.872	1.07	23.04	0.53	310.1±87.3
610	54.17	0.07066	10.583	3.05	63.04	4.28	373.4±15.2
635	44.00	0.03103	12.742	6.13	81.52	11.74	390.9±9.3
650	39.95	0.01953	12.055	8.70	88.01	17.66	383.8±3.2
670	38.80	0.01630	11.502	12.12	90.00	20.19	381.3±3.7
685	38.61	0.01404	11.302	11.42	91.63	23.03	385.8±3.1
700	39.30	0.01377	11.306	6.89	91.98	23.49	393.3±4.0

TABLE 2 (*concluded*)

Release temp. (°C)	$(^{40}Ar/^{39}Ar)_{meas}$[a]	$(^{36}Ar/^{39}Ar)_{meas}$[a]	$(^{37}Ar/^{39}Ar)_{corr}$[b]	^{39}Ar (% of total)	^{40}Ar (%, nonatmos.)[c]	$^{36}Ar_{calc}$ (%)	Apparent age (ma)[d]
710	38.28	0.00990	11.409	8.40	94.78	32.95	394.6±2.9
720	38.28	0.01188	11.327	6.56	93.23	27.27	388.7±3.3
735	36.36	0.00602	10.798	23.26	97.51	51.30	386.4±2.6
745	36.44	0.00694	10.491	2.58	96.70	43.23	384.1±11.1
755	37.08	0.00273	10.161	4.86	100.04	106.49	420.1±8.3
765	39.82	0.00719	9.847	1.78	96.66	39.16	415.6±19.2
780	43.55	0.03052	10.094	1.19	81.16	9.46	385.0±16.7
800	49.48	0.05812	10.292	0.95	66.98	5.07	363.4±22.1
Fusion	217.41	0.08667	9.914	1.05	20.63	0.48	475.9±67.3
Total	41.85	0.02421	11.153	100.00	90.19	32.72	387.7±7.9
			Sample 4C: $J = 0.008643$				
475	249.26	0.36540	11.360	0.89	57.05	0.85	1453.2±48.8
525	169.20	0.22713	7.616	1.01	60.69	0.91	1150.1±45.6
575	85.76	0.16444	12.160	0.7	44.47	2.01	517.4±91.5
625	55.33	0.08235	14.860	1.16	58.16	4.91	446.4±61.3
650	47.95	0.05636	15.926	1.32	67.32	7.69	451.4±42.4
670	38.35	0.02618	16.022	3.91	83.17	16.65	443.2±8.7
700	35.45	0.01826	15.787	12.02	88.34	23.52	436.0±4.5
720	35.36	0.01846	16.020	10.94	88.20	23.60	434.4±5.1
735	38.98	0.03321	16.030	6.32	78.00	13.13	432.8±5.6
750	35.94	0.02266	15.950	6.92	84.83	19.15	433.6±5.8
770	34.25	0.01568	15.868	9.07	90.18	27.53	430.8±5.4
790	34.21	0.01189	15.776	19.27	93.42	36.09	444.0±2.3
810	36.60	0.01369	15.677	14.22	92.37	31.15	466.5±5.0
Fusion	41.07	0.02662	15.606	12.17	83.89	15.95	474.4±5.3
Total	40.32	0.02632	15.657	100.00	86.89	24.23	461.7±8.5

[a]Measured.
[b]Corrected for postirradiation decay of ^{37}Ar (35.1 day half-life).
[c]Calculated using relationship $[^{40}Ar_{tot} - (^{36}Ar_{atmos})(295.5)]/^{40}Ar_{tot}$.
[d]Calculated using correction factors of Dalrymple *et al.* (1981); 2σ, intralaboratory errors.

TABLE 3. $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlations for hornblende concentrates from units of the Cape North area, Cape Breton Highlands, Nova Scotia

Sample	Increments (°C)	% ^{39}Ar released	Age[a]	$^{40}Ar/^{36}Ar$[b]	MSWD
		CAPE NORTH GROUP			
1	695–820	87.44	383.3±2.2	335.9±24.3	0.57
8	660–820	90.64	381.6±0.6	264.9±13.6	0.28
10	645–745	90.1	390.8±3.0	285.9±12.6	1.02
		MONEY POINT GROUP			
3B	650–735	83.48	384.4±1.6	282.9±26.3	1.2
4C	700–770	45.27	434.6±3.7	264.7±17.9	2.2

[a]Based on the inverse abcissa intercept.
[b]Inverse ordinate intercept.

of the time of crystallization of the rock. Closure temperatures for U–Pb in monazite have been estimated at between 640 and 750°C (Parrish 1990; Mezger *et al.* 1991), temperatures just above peak metamorphic conditions in the Cape North area (Fig. 5). Thus, the 414 ± 3 Ma age probably closely dates the intrusion of the Cape North granite.

$^{40}Ar/^{39}Ar$

The five hornblende concentrates record variable apparent ages in the relatively small volume increments evolved at very low and very high experimental temperatures. This is matched by marked fluctuations in apparent K/Ca ratios, which suggest experimental evolution of argon from compositionally distinct and variably retentive phases. These could be represented by (1) very minor, optically undectable mineralogical contaminants in the amphibole concentrates; (2) petrographically unresolvable exsolution or compositional zonation within constituent amphibole grains; (3) minor chloritic replacement of amphibole; and (or) (4) intracrystalline inclusions. In general, >85% of the total ^{39}Ar evolved from each concentrate is characterized by similar apparent K/Ca ratios, indicating experimental evolution of gas at intermediate temperatures

TABLE 4. $^{40}Ar/^{39}Ar$ analytical data for incremental heating experiments on muscovite concentrates from the area of Cape North, Cape Breton Highlands, Nova Scotia

Release temp. (°C)	$(^{40}Ar/^{39}Ar)_{meas.}$[a]	$(^{36}Ar/^{39}Ar)_{meas.}$[a]	^{39}Ar (% of total)	^{40}Ar (%, nonatmos.)[b]	Apparent age (Ma)[c]
		CAPE NORTH GROUP			
		Sample 9: J = 0.008511			
475	29.24	0.01172	3.01	88.14	357.7±4.5
500	28.30	0.00511	1.93	94.64	370.4±3.7
520	27.65	0.00288	4.52	96.90	370.6±3.1
535	27.45	0.00241	7.96	97.39	369.8±1.2
550	27.26	0.00171	15.65	98.12	369.9±0.6
570	27.11	0.00173	15.25	98.10	368.1±0.7
590	27.11	0.00143	14.00	98.42	369.2±0.9
610	27.20	0.00204	7.65	97.77	368.0±2.9
630	27.24	0.00181	5.68	98.01	369.3±3.2
655	27.22	0.00209	6.86	97.71	368.0±2.6
680	27.23	0.00140	5.32	98.46	370.8±3.3
705	27.33	0.00166	7.27	98.19	371.1±2.4
735	27.53	0.00254	4.36	97.25	370.3±3.2
770	33.22	0.02688	0.48	76.13	351.7±11.9
Fusion	76.91	0.14573	0.06	44.02	456.8±256.7
Total	27.40	0.00243	100.00	97.46	369.0±1.8
Total without 475–520°C, 770°C, and fusion data			96.44		369.3±1.5
		CAPE NORTH GRANITE			
		Sample 2: J = 0.006681			
450	55.49	0.08627	0.36	54.03	329.4±35.4
500	40.01	0.01470	3.01	89.06	385.3±4.2
515	36.76	0.00568	7.17	95.33	379.5±0.9
530	37.13	0.00610	7.80	95.05	381.9±1.1
540	36.85	0.00521	15.48	95.72	381.7±1.8
550	37.25	0.00680	8.75	94.51	381.1±1.9
560	36.54	0.00500	6.45	95.85	379.4±1.3
575	36.65	0.00446	6.57	96.30	382.0±2.2
590	36.75	0.00496	5.59	95.91	381.4±2.0
615	36.89	0.00653	4.54	94.67	378.4±1.8
645	36.99	0.00700	4.79	94.31	377.9±2.3
675	36.47	0.00461	10.43	96.16	379.8±1.5
705	36.13	0.00296	16.32	97.48	381.2±1.0
Fusion	36.96	0.00719	2.72	94.15	377.1±2.6
Total	36.88	0.00573	100.0	95.41	380.5±1.5
Total without 450°C, 550°C, and fusion data			99.64		380.6±1.3
		MONEY POINT GROUP			
		Sample 3D: J = 0.006681			
450	36.30	0.03834	0.67	68.68	277.9±16.3
490	37.97	0.00951	1.74	92.50	380.3±3.6
510	35.67	0.00390	3.47	96.66	373.9±2.3
525	36.39	0.00631	3.77	94.77	374.0±1.4
540	35.55	0.00390	5.37	96.66	372.9±1.7
550	35.32	0.00279	17.73	97.56	373.8±0.8
560	35.51	0.00266	5.23	97.68	376.0±1.1
575	35.49	0.00295	5.87	97.44	374.9±1.8
590	35.41	0.00220	7.55	98.06	376.4±1.5
620	35.51	0.00300	7.55	97.40	375.0±1.0
650	35.53	0.00294	7.70	97.45	375.4±1.5
680	35.50	0.00248	8.03	97.83	376.4±0.9
705	35.52	0.00285	8.56	97.52	375.6±1.3
735	35.38	0.00202	10.62	98.21	376.6±1.1
770	35.74	0.00244	5.78	97.88	378.9±1.0
Fusion	48.40	0.04601	0.36	71.84	376.9±14.4
Total	35.60	0.00339	100.0	97.12	374.8±1.2
Total without 450°C, 490°C, and fusion data			97.23		375.3±1.0
		SAMPLE 4B: J = 0.009148			
450	30.24	0.02474	0.82	75.82	343.5±7.8
500	28.46	0.00954	0.94	90.07	380.0±15.9

TABLE 4 (*continued*)

Release temp. (°C)	$(^{40}Ar/^{39}Ar)_{meas}$[a]	$(^{36}Ar/^{39}Ar)_{meas}$[a]	^{39}Ar (% of total)	^{40}Ar (%, nonatmos.)[b]	Apparent age (Ma)[c]
515	26.24	0.00358	5.08	95.95	373.9±2.7
530	26.17	0.00352	3.29	96.00	373.3±4.5
545	25.97	0.00245	5.42	97.19	374.7±2.1
560	25.76	0.00162	3.91	98.12	375.2±3.8
585	25.79	0.00204	3.44	97.64	374.0±3.1
610	25.77	0.00293	3.69	96.62	370.1±2.8
640	25.77	0.00184	5.86	97.87	374.5±2.0
670	25.66	0.00168	5.63	98.04	373.6±1.7
700	25.74	0.00163	4.59	98.10	374.9±1.5
735	25.78	0.00206	5.10	97.62	373.8±1.9
770	25.90	0.00254	6.64	97.08	373.5±1.6
790	26.31	0.00335	6.72	96.21	375.8±1.5
810	26.71	0.00504	6.82	94.41	374.5±1.7
830	26.54	0.00434	31.61	95.14	375.0±0.8
855	96.54	0.24585	0.44	24.75	356.6±28.5
Fusion	2014.46	6.90210	0.02	−1.24	−468.8±631.0
Total	26.83	0.00557	100.00	95.79	374.0±3.4
Total without 450°C, 500°C, 855°C, and fusion data				97.79	374.3±1.6
		Sample 5: J = 0.009051			
450	26.85	0.01555	1.96	82.87	330.9±4.0
495	28.64	0.00758	1.69	92.17	386.5±3.9
515	26.59	0.00285	22.47	96.81	377.8±0.6
530	26.29	0.00258	5.46	97.08	374.9±1.0
545	26.21	0.00271	14.64	96.92	373.3±0.7
560	25.82	0.00191	11.11	97.79	371.2±1.8
575	25.92	0.00221	7.08	97.46	371.4±2.0
595	26.02	0.00268	7.15	96.93	370.9±1.8
615	26.05	0.00342	4.88	96.10	368.5±3.0
640	26.08	0.00224	3.77	97.44	373.5±3.2
670	26.09	0.00340	4.21	96.12	369.0±3.0
700	26.12	0.00377	6.72	95.71	367.9±2.7
730	26.21	0.00325	7.48	96.31	371.2±2.8
760	29.25	0.03775	1.16	61.84	273.5±56.1
790	45.67	0.07894	0.15	48.95	322.4±76.3
820	70.91	0.13433	0.05	44.02	448.9±122.4
Fusion	95.48	0.30720	0.04	4.96	75.7±196.9
Total	26.36	0.00380	100.00	95.96	371.4±2.9
Total without 450−515°C, 760−820°C, and fusion data			72.49		371.3±1.3
		Sample 7: J = 0.009179			
450	30.93	0.04550	0.39	56.54	268.6±12.3
500	24.83	0.00610	2.25	92.72	345.8±3.7
515	25.03	0.00216	3.37	97.43	364.4±2.1
530	25.06	0.00259	5.47	96.93	363.1±1.6
545	25.10	0.00172	12.12	97.95	367.2±0.7
560	24.98	0.00183	9.60	97.81	365.1±0.8
580	24.98	0.00172	8.78	97.94	365.4±1.0
600	24.92	0.00148	8.80	98.22	365.7±1.5
625	24.92	0.00173	6.52	97.92	364.7±1.7
650	24.89	0.00179	4.55	97.85	364.1±1.9
675	24.95	0.00225	4.14	97.31	363.0±2.1
700	24.97	0.00177	7.78	97.88	365.2±1.9
730	24.91	0.00143	10.66	98.28	365.7±1.5
760	24.85	0.00123	11.98	98.52	365.7±2.0
Fusion	25.02	0.00157	3.60	98.13	366.7±2.2
Total	24.98	0.00197	100.00	97.68	364.6±2.0
Total without 450°C, 500°C, and fusion data			97.36		365.3±1.8
		RELAY STATION GRANITE Sample 6: J = 0.008661			
475	32.02	0.01736	2.92	83.97	377.7±5.1
500	29.63	0.00571	8.73	94.29	390.9±2.6

TABLE 4 (*concluded*)

Release temp. (°C)	$(^{40}Ar/^{39}Ar)_{meas}$[a]	$(^{36}Ar/^{39}Ar)_{meas}$[a]	^{39}Ar (% of total)	^{40}Ar (%, nonatmos.)[b]	Apparent age (Ma)[c]
540	28.16	0.00318	24.07	96.68	383.6±1.7
570	28.25	0.00321	16.08	96.62	382.8±2.8
650	27.71	0.00253	32.61	97.28	378.5±1.8
700	28.08	0.00335	14.14	96.45	380.1±1.9
750	30.60	0.01242	1.01	87.99	378.4±20.1
Fusion	86.53	0.19633	0.43	32.96	398.2±55.3
Total	28.60	0.00455	100.00	85.89	382.2±2.5
Total without 475°C, 510°C, 750°C, and fusion data			87.92		381.5±2.1
		WHITE POINT GRANITE			
		Sample 11: J = 0.008975			
450	35.35	0.04858	0.43	59.36	311.3±30.9
500	28.19	0.01053	2.72	88.95	366.2±4.2
515	26.55	0.00487	6.64	94.56	366.6±1.3
535	26.28	0.00558	7.66	93.70	360.3±1.8
555	25.85	0.00390	11.11	95.51	361.1±1.2
575	25.78	0.00381	11.07	95.61	360.5±1.2
610	25.74	0.00374	10.72	95.68	360.3±1.9
660	25.81	0.00400	12.71	95.40	360.2±2.3
700	25.48	0.00334	15.98	96.10	358.4±2.0
750	25.39	0.00286	17.48	96.65	359.1±2.1
Fusion	35.49	0.03804	3.48	68.31	355.1±6.5
Total	26.21	0.00537	100.00	94.34	360.1±2.2
Total without 450–515°C and fusion data			86.73		359.8±1.9
		Sample 12: J = 0.008889			
450	33.70	0.03500	1.50	69.29	340.3±17.1
500	27.72	0.00666	4.03	92.88	371.8±3.2
520	27.39	0.00738	12.32	92.01	364.7±1.4
535	26.48	0.00454	14.42	94.91	363.8±1.0
550	26.04	0.00330	14.22	96.23	362.9±1.5
570	26.10	0.00363	13.39	95.87	362.3±2.0
590	26.27	0.00419	8.92	95.26	362.4±2.2
610	26.37	0.00490	9.83	94.49	361.0±2.9
630	26.19	0.00486	8.03	94.50	358.8±4.3
655	26.18	0.00410	6.14	95.35	361.6±3.0
685	26.20	0.00403	3.89	95.43	362.0±6.4
715	26.29	0.00350	2.96	96.04	365.3±4.4
Fusion	28.59	0.01148	0.35	88.13	364.7±37.5
Total	26.56	0.00511	100.00	94.42	362.6±2.7
Total without 450°C, 500°C, 715°C, and fusion data			87.27		362.4±2.1

[a]Measured.
[b]Calculated using relationshp $[^{40}Ar_{tot} - (^{36}Ar_{atmos})(295.5)]/^{40}Ar_{tot}$.
[c]Calculated using correction factors of Dalrymple *et al.* (1981); 2σ, intralaboratory errors.

occurred from compositionally uniform populations of intracrystalline sites. Within sample 8 intermediate-temperature gas fractions record nearly identical apparent ages and yield a well-defined, 380 4 ± 2.4 Ma plateau. Within samples 1, 3B, and 10 intermediate-temperature gas fractions record generally similar apparent ages, but they do not rigorously define a plateau. However, the intermediate-temperature analytical data correspond to well-defined isotope correlations (MSWD < 2.0) that yield ages (383.3 ± 2.2, 384.4 ± 1.6, and 390.8 ± 3.0 Ma) similar to the plateau age defined by sample 8. The isotope correlations yield inverse ordinate intercepts ($^{40}Ar/^{36}Ar$ ratios) that are similar to present-day atmospheric ratios indicating an absence of significant extraneous argon components. The ca. 380–390 Ma ages recorded by the three amphibole concentrates are therefore interpreted as dating the last cooling through temperatures required for intracrystalline retention of argon within constituent amphibole grains. Harrison (1981) indicated that closure temperatures for argon systems within igneous hornblende are not significantly affected by compositional variations. He suggested values of approximately 500 ± 25°C are appropriate for the range of cooling rates likely to be encountered in most geological settings. The discordant, saddle-shaped spectrum displayed by sample 4C is inferred to indicate the presence of significant extraneous argon. Therefore, no geologically meaningful age may be derived from this spectrum. This is borne out by the fact that the 434.6 ± 3.7 Ma hornblende isotope correlation age is older than the U–Pb zircon protolith age of 427.5 ± 4 Ma.

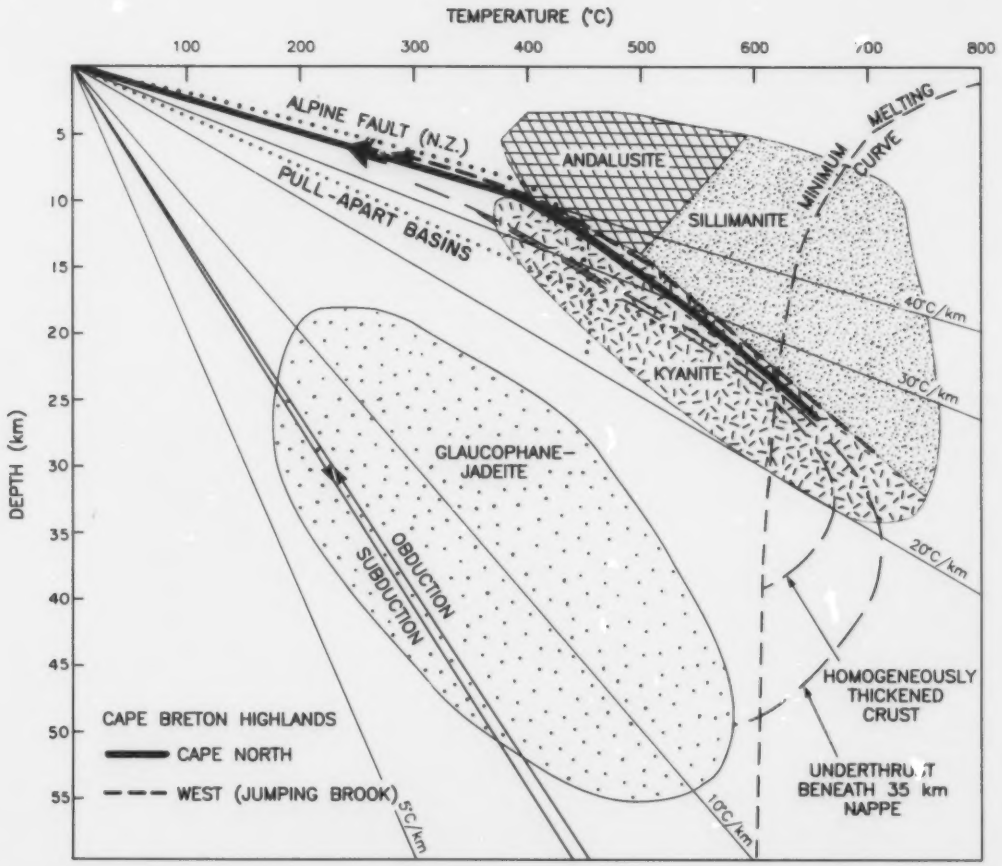

FIG. 5. Pressure (expressed as depth) vs. temperature diagram, showing the pressure–temperature paths for the Cape North area (Macdonald and Smith 1980), the Jumping Brook area in the western Cape Breton Highlands (Plint and Jamieson 1989), pull-apart basins (Nilsen and McLaughlin 1985; Weir and Furlong 1987), the Alpine Fault in New Zealand (Cooper 1980; Koons 1987), and models for overthrusting and homogeneously thickened crust relative to selected metamorphic mineral assemblages and reactions (after England and Thompson 1984). Overthrust thickness = 35 km, with average continental heat flux (heat source distribution II) = 60 $mW \cdot m^{-2}$; surface heat flux and conductivity = 2.25 $W \cdot m^{-1} \cdot k^{-1}$; homogeneous shortening by a factor of 2, with continental heat flux (heat distribution III) = 75 $mW \cdot m^{-2}$, and surface heat flux and conductivity = 3 $W \cdot m^{-1} \cdot k^{-1}$.

The nine muscovite concentrates record well-defined plateau ages. Those from the Cape North and Money Point groups range between 365.3 ± 1.8 and 375.3 ± 2.0 Ma. Muscovite concentrates from the Cape North and Relay Station granite plutons record slightly older plateau ages (380.6 ± 1.3 and 381.5 ± 2.1 Ma, respectively). Those from the White Point pluton record younger plateau ages of 362.4 ± 2.1 and 359.8 ± 1.9 Ma. The plateau ages are interpreted as dating the last cooling through those temperatures required for intracrystalline retention of argon. Although not fully calibrated experimentally, using the preliminary data of Robins (1972) in the diffusion equations of Dodson (1973) indicates muscovite closure temperatures of approximately 350–400°C. These are comparable with those suggested for muscovite on the basis of empirical comparisons with other mineral isotopic systems (e.g., Purdy and Jäger 1976).

It is interesting to compare the $^{40}Ar/^{39}Ar$ biotite data of Reynolds *et al.* (1989) in the context of our results. Harrison *et al.* (1985) indicated that temperatures required for intracrystalline retention of argon in biotite were sensitive to mineralogical composition and increased markedly with increasing Mg/Fe ratios. They suggested a potential range of 280–340°C for a range of reasonable cooling rates. Thus, one would expect biotite argon ages to be younger than those recorded by muscovite and hornblende. However, the biotite sample (23) of Reynolds *et al.* (1989) yielded a discordant spectrum with a total-gas age of ca. 429 Ma, which is anomalously old (probably due to contamination with intracrystalline extraneous argon components). The same conclusion may also explain the discordant spectra displayed by the other biotite results presented by Reynolds *et al.* (1989), which therefore calls into question the geological significance of these data.

Geological significance

A 427.5 ± 4 Ma extrusive age for rhyolite within the Money Point Group indicates that deposition of host sedimentary units occurred near the base of the Wenlockian Series of the Silurian (Figs. 5, 6) (based on the International Union of Geological Sciences time scale; Cowie and Bassett 1989). However, in the absence of other age constraints, the total time span for deposition of the entire Money Point Group is

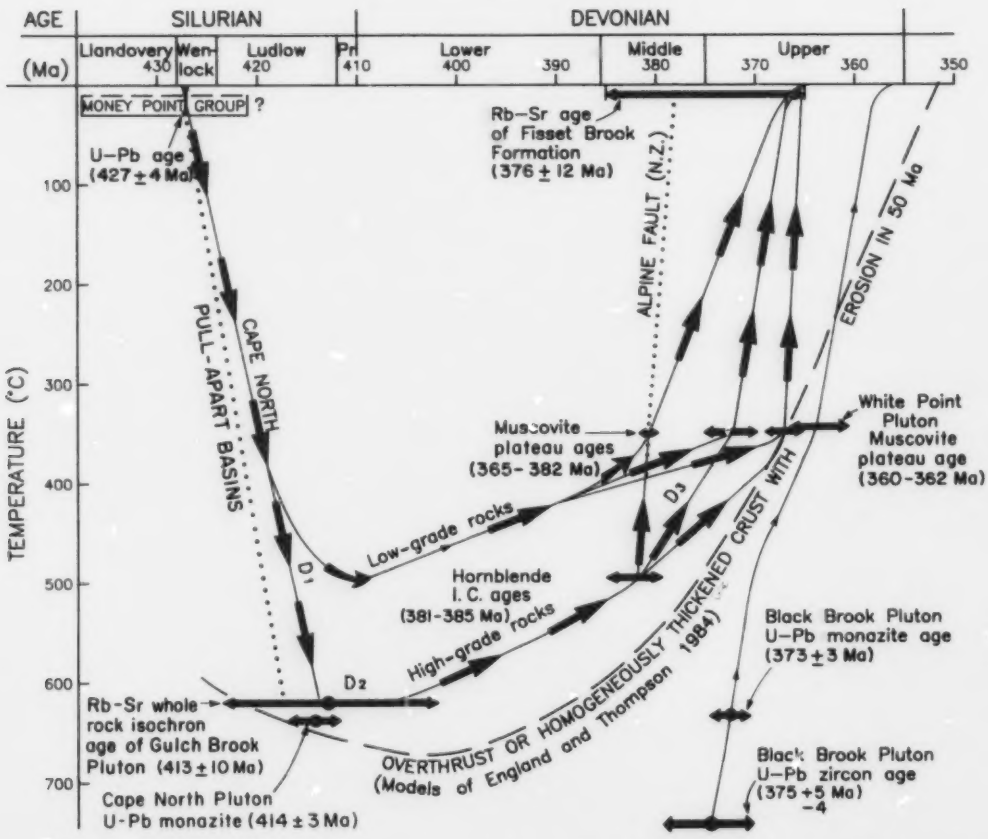

FIG. 6. Temperature vs. time diagram, showing temperature–time paths for the Cape North area and White Point – Black Brook pluton relative to pull-apart basins, the Alpine Fault in New Zealand, and models for overthrusting and homogeneously thickened crust (sources as in Fig. 4). See text for geochronological data sources.

unknown. Unmetamorphosed volcanic rocks exposed on Ingonish Island have been dated at 412 ± 15 Ma (Rb–Sr whole-rock isochron with MSWD = 10.4; Keppie and Halliday 1986) and could represent an outlier of the Money Point Group. The ca. 428 Ma age for formation of the Money Point Group is similar to that reported for the lithostratigraphic correlative Sarach Brook metamorphic suite (434^{+7}_{-4} Ma; U–Pb zircon age; Dunning *et al.* 1990*a*) and the Jumping Brook complex (439 ± 7 Ma; U–Pb zircon age for a feeder dyke to the Jumping Brook complex; Currie *et al.* 1982) exposed in the southern and western Cape Breton Highlands, respectively (Fig. 7). The Money Point Group is also lithostratigraphically similar to the La Poile Group exposed in southern Newfoundland, which has yielded U–Pb zircon crystallization ages between 428 ± 6 and 420^{+8}_{-2} Ma (Dunning *et al.* 1990*b*). Considered together these ages suggest that the volcanism lasted throughout most of the Silurian.

The ca. 428 Ma crystallization age provides a maximum age for tectonothermal events recorded within the Money Point and Cape North groups. In addition, the 414 ± 3 Ma U–Pb monazite age closely dates the time of intrusion of the Cape North granite, which was intruded immediately after the metamorphic climax: 650°C and 6 kbar (1 kbar = 100 MPa) (Figs. 5, 6) (Macdonald and Smith 1980). This is supported by the 413 ± 10 Ma Rb–Sr, whole-rock isochron age reported for the late-D_2, Gulch Brook pluton (Fig. 3) (Keppie and Halliday 1986).

The $^{40}Ar/^{39}Ar$ hornblende plateau ages (ca. 384–382 Ma) suggest that postmetamorphic cooling through approximately 500°C was synchronous across the area (Figs. 2, 3, 6). Considering a ca. 414 ± 3 Ma emplacement age for the Cape North pluton and the hornblende cooling ages, a cooling rate of approximately 5°C/Ma is indicated in the temperature interval 650–500°C (Fig. 6). Relatively rapid cooling between approximately 500 and 350°C (approx. 9–55°C) is indicated by the ca. 382–365 Ma plateau ages recorded by muscovite (Figs. 3, 6). Differences in muscovite plateau ages appear in constrasting rock types and are best illustrated by the ca. 365 Ma plateau age for decussate muscovite developed in country rocks adjacent to the ca. 382 Ma muscovite plateau age in the Relay Station pluton (these samples are only 20 m apart). These differences in the muscovite cooling ages may reflect different closure temperatures for igneous and metamorphic muscovite. Alternatively, they may be due to slight variations in the rate of cooling between 500 and 350°C across the area (Fig. 6). The Fisset Brook Formation was deposited unconformably over metamorphic rocks of the Cape Breton Highlands (Fig. 2) and has yielded Late Devonian spores (Smith and Macdonald 1981) and gave a Rb–Sr whole-rock isochron age of 376 ± 12 Ma (Cormier and Kelley 1964;

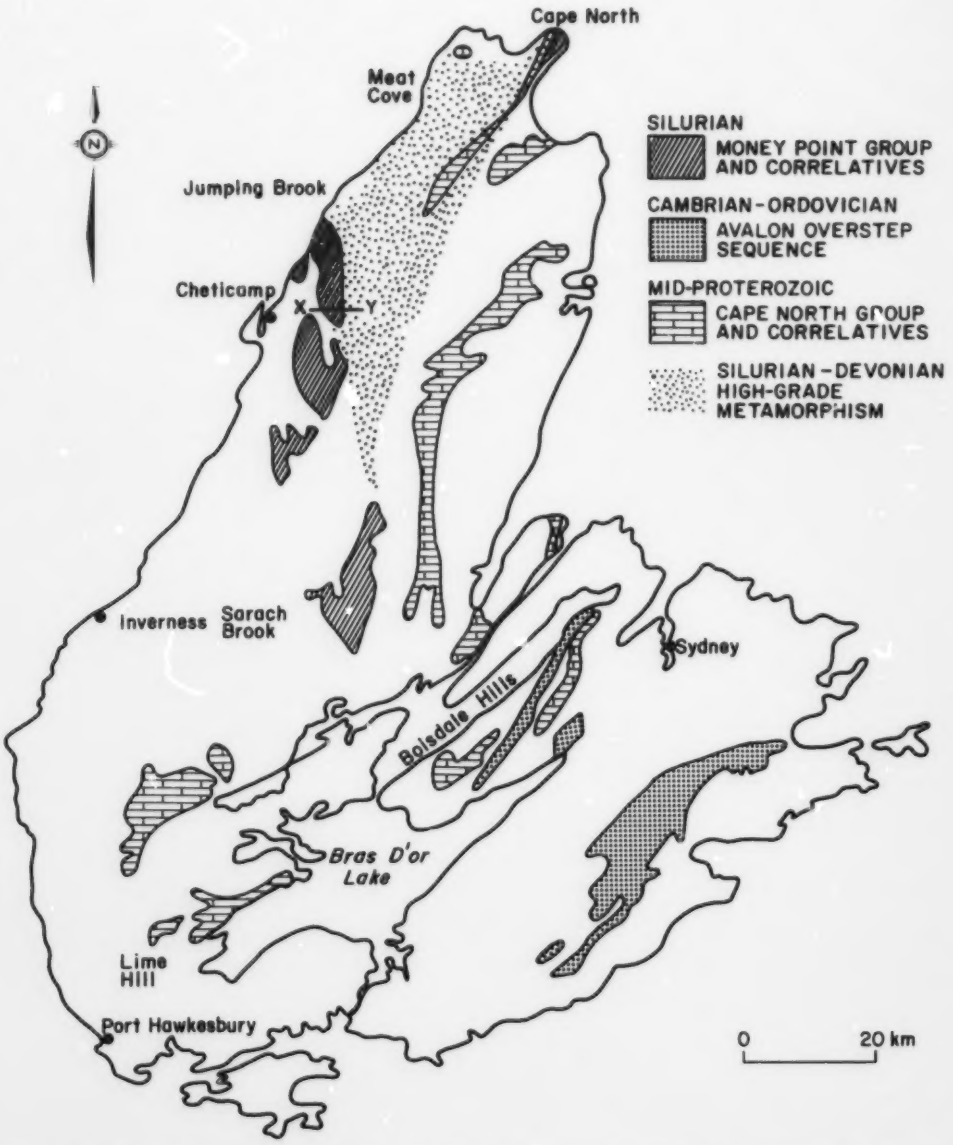

FIG. 7. Map of Cape Breton Island, showing the distribution of Silurian volcano-sedimentary units, Cambrian–Ordovician overstep sequence defining the Avalon Composite Terrane, Middle–Late Proterozoic George River Group and correlatives, and Silurian–Devonian high-grade metamorphism. X–Y is the location of cross section shown in Fig. 8.

recalculated by Keppie and Smith 1978). This indicates that uplift, erosion, and cooling between 350°C and ambient surface temperatures in the Cape North area must have continued at a similar rapid rate (Fig. 6).

Intrusion of the White Point pluton at ca. 375 Ma (Dunning *et al.* 1990*a*) was followed by cooling through 350°C at ca. 360–362 Ma ($^{40}Ar/^{39}Ar$ muscovite plateau ages), indicating a rate of cooling between approximately 750–640°C (zircon and monazite closure temperatures) and 350°C of approximately 13–23°C/Ma (Fig. 6). The White Point pluton is nonconformably overlain by Tournaisian Horton Group and indicates that uplift, erosion, and cooling continued at approximately 46–64°C/Ma until ambient surface temperatures were reached at ca. 355 Ma (Fig. 6) (base of the Tournaisian: Cowie and Bassett 1989).

The pressure–temperature–time ($P-T-t$) path derived for the Cape North area is similar to that proposed by Plint and Jamieson (1989) in the Cheticamp area on the western side of the Cape Breton Highlands (Figs. 5, 6). Plint and Jamieson (1989) explained their $P-T-t$ path by either instantaneous overthrusting of a 20 km thick crustal slab immediately followed by erosion, or instantaneous overthrusting of a 20 km crustal slab followed by a delay of 25 Ma prior to the onset of rapid uplift (4 km/Ma) and a resultant isobaric cooling. The first alternative reproduced the $P-T$ path but failed to conform to the observed time data. The second alternative failed

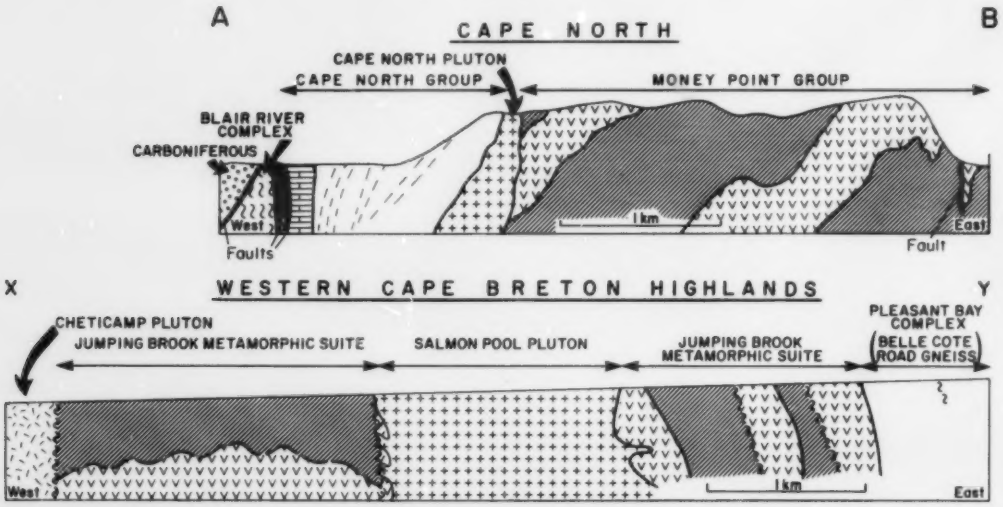

FIG. 8. Cross sections across the Cape Breton Highlands. A–B across the Cape North area, modified after Macdonald and Smith (1980); see Fig. 3 for location. X–Y across the western Cape Breton Highlands near Cheticamp, modified after Craw (1984); see Fig. 7 for location.

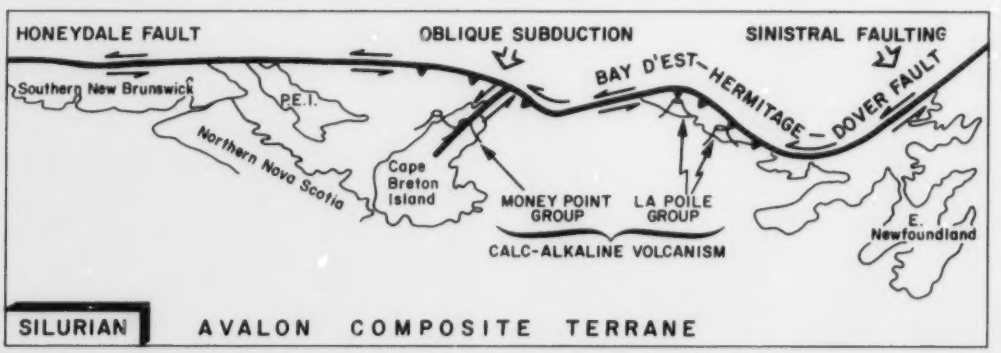

FIG. 9. Tectonic model for the sinistral accretion of the Avalon Composite Terrane with Laurentia during the Silurian – Early Devonian.

to reproduce the $P-T$ path but more closely approximated the time data. However, theoretical models described by England and Thompson (1984) indicate that such $P-T-t$ paths may be produced by either overthrusting or homogeneously thickened crust (Figs. 5, 6). Thus other criteria are required to differentiate between the contrasting tectonic models.

The major structure of the Cape Breton Highlands is a north-trending, vertically dipping, high metamorphic grade central zone bounded by outward-verging asymmetric to recumbent, low metamorphic grade marginal zones (Figs. 3, 7, 8) (Macdonald and Smith 1980; Craw 1984). Such a configuration is typical of positive flower structures in which the central part of a transcurrent fault zone is thrust up and over both marginal areas. This is consistent with the subhorizontal sinistral movement inferred for the D_{1-2} deformation in the Cape North area. On the other hand, an overthrust model is not consistent with field relationships because (1) high-pressure metamorphic assemblages in low-grade units below the thrust (Money Point Group and Jumping Brook complex) do not occur; and (2) the calc-alkaline nature of the volcanic rocks in both the Money Point Group and the Jumping Brook complex (Macdonald and Smith 1980; Jamieson *et al.* 1990) implies that the Cape Breton Highlands were situated within an upper plate in a convergent boundary regime.

Modern transpressional regimes involve either homogeneous thickening of the crust–lithosphere followed by rapid uplift and erosion or rapid subsidence of a pull-apart basin followed by rapid uplift and erosion. Rates of subsidence and sedimentation in pull-apart basins range up to 3 km/Ma over about 20 Ma in the Ridge Basin between the dextral transcurrent San Andreas and San Gabriel faults in southern California (Nilsen and McLaughlin 1985). These rates are comparable to burial rates experienced by the Cape North area. A modern analogue for retrograde parts of the Cape North $P-T-t$ path has been recorded adjacent to the dextral transpressive Alpine Fault in southern New Zealand (Cooper 1980; Koons 1987). These analogues suggest that a transpressive regime is compatible with the $P-T-t$ history of the Cape Breton Highlands.

Regional implications

Silurian–Devonian tectonothermal events synchronous with those in the Cape North area have been recorded in southern Newfoundland (Fig. 1) (Dunning *et al.* 1990*b*). In

southern Newfoundland, pre-, syn-, and posttectonic granitic intrusions have yielded U–Pb zircon ages of 429^{+5}_{-3}, 415 ± 2, and 396^{+6}_{-3} Ma, respectively (Dunning *et al.* 1990*b*). In this area, the Silurian La Poile Group was thrust northwest over the Ordovician Bay du Nord Group (part of the Dunnage Zone) along the Bay d'Est Fault (O'Brien 1989) (Fig. 9). As in the Money Point Group, polyphase deformation of the La Poile Group was accompanied by greenschist to upper amphibolite facies metamorphism. The La Poile Group unconformably overlies low-grade metasedimentary rocks containing ca. 593 Ma detrital zircon in horizons interbedded with metavolcanic rocks that have yielded a U–Pb magmatic zircon age of 544 ± 5 Ma (Dunning and O'Brien 1989). These rocks unconformably overlie paragneiss, orthogneiss (dated at 686^{+33}_{-15} Ma; protolith U–Pb magmatic zircon age; Dunning and O'Brien 1989), migmatite, and amphibolitic gneiss that were polydeformed and metamorphosed under amphibolite-facies conditions at 579 ± 10 Ma (U–Pb metamorphic titanite age; Dunning and O'Brien 1989) and intruded by granite at 563 ± 4 and 499 ± 4 Ma (U–Pb magmatic zircon age; Dunning and O'Brien 1989). The area south of the Bay d'Est Fault was considered part of the Burgeo Terrane by Keppie and Dallmeyer (1989). Although the Burgeo Terrane lacks the distinctive Avalonian, Cambrian–Ordovician overstep sequence, it has marked affinities with the Avalon Composite Terrane (Dunning and O'Brien 1989; Keppie *et al.* 1991*a*).

The Avalonian affinity of these rocks is better preserved in Cape Breton Island where the Cape North Group may be lithostratigraphically, geochemically, and isotopically correlated with the Meat Cove metasediments and the type George River Group (Fig. 7) (Keppie 1979, 1990; Hill 1990; Sangster *et al.* 1990). In southern Cape Breton Island (Boisdale Hills), the George River Group is unconformably or disconformably overlain by Middle Cambrian rocks typical of the Avalonian overstep sequence, which contains pebbles of deformed and metamorphosed George River Group (Fig. 7) (Hutchinson 1952; Helmstaedt and Tella 1973; Keppie 1989). Thus, by extension all of Cape Breton Island and the Burgeo Terrane on southern Newfoundland should be considered integral parts of the Avalon Composite Terrane. Therefore, the recorded Silurian–Devonian tectonothermal events may represent orogenic activity associated with the accretion of the Avalon Composite Terrane with the Dunnage and Gander zones (Keppie 1989). Similar age constraints for the accretion of the Avalon Composite Terrane are recorded along the Dover – Hermitage Bay Fault that defines the western boundary of the Avalon Composite Terrane in eastern Newfoundland (Figs. 1, 9). Here, the age of accretionary fabrics is constrained by (1) intrusion of the pre- to syntectonic Cape Freels pluton dated at 414 ± 5 Ma (Rb–Sr whole-rock isochron; Bell *et al.* 1977); (2) a 397 ± 5 Ma $^{40}Ar/^{39}Ar$ hornblende plateau age for gneisses adjacent to the Dover Fault (Dallmeyer *et al.* 1981); and (3) postaccretionary intrusion of the Ackley stitching pluton dated at 375 ± 4 Ma ($^{40}Ar/^{39}Ar$ hornblende age; Kontak *et al.* 1988). Kinematic analysis of ductile structures associated with accretion indicates sinistral shearing within the Dover – Hermitage Bay Fault (Fig. 9) (Piasecki 1988). This contrasts with northwest-thrusting experienced along the Bay d'Est Fault in southern Newfoundland (Fig. 9) (O'Brien 1989). The change in fault kinematics may be due to the irregular western boundary of the Avalon Composite Terrane and therefore relate to the strike of the boundary. Both the Dover – Hermitage Bay and the Aspy – Wilkie Brook faults have similar trends to each other and were characterized by sinistral transcurrent kinematics. These observations can be explained by tectonic models involving sinistral accretion of the Avalon Composite Terrane with Laurentia during the Silurian and Early Devonian (Fig. 9). In such models, northeast-trending boundaries would be approximately parallel to transform faults, and east-trending boundaries would be parallel to oblique subduction zones. Limited associated subduction would also explain the calc-alkaline nature of the volcanic rocks in the Money Point Group and correlative units. Thus, deposition of the calcalkaline, volcano-sedimentary Money Point Group and its subsequent deformation and metamorphism may be explained in terms of oblique sinistral accretion of the Avalon Composite Terrane.

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